ΛCDM cosmology from visible matter only

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Abstract

We discuss physical interpretation of ΛCDM cosmology from a Machian model of the universe containing nothing but visible matter (ordinary matter, radiation). The Friedmann equation can be derived from a Machian definition of energy, whereby both kinetic and potential energy of a particle are related to all cosmic matter-energy within the particle's gravitational horizon. The distance to this horizon thus appears as a parameter in all forms of matter-energy density. From conservation of Machian energy it follows that all different types of matter-energy are uniformly characterized by $\rho \propto a^{-1}$, i.e., by a constant deceleration $q = -1/2$. This coincides with relative densities $\Omega_m = 1/3$ and $\Omega_\Lambda = 2/3$ of ΛCDM. Thus the Machian cosmological model matches present relative densities of ΛCDM, without invoking dark components.

The ΛCDM cosmological model matches a wide range of observations quite accurately. Despite this success, the model relies on the existence of hypothesized dark matter and dark energy, so its physical justification is poor. We therefore consider physical interpretation of the (flat) ΛCDM model with Friedmann equation

$$\frac{\dot{a}^2}{a^2} = \frac{8}{3}\pi G(\rho + \rho_\Lambda), \tag{1}$$

where a is the scale factor, ρ is the density of the various matter sources (radiation, dust) and ρ_Λ is vacuum energy density.

The constant ρ_Λ causes accelerated expansion, but its presence lacks physical ground. At the present epoch the matter density ρ is mainly dust (both baryonic and dark). The density of dust dilutes as a^{-3}, therefore causes deceleration, which is physically attributed to the attractive force of gravity between cosmic matter, be it mostly dark. This view on cosmic matter (deceleration by attraction) is supported by the well known Newtonian interpretation of the dust term on the basis of the shell theorem when applied to an infinite homogeneous isotropic universe, causing the field inside a spherical cavity to be uniformly zero. Hence, a particle at the surface of an arbitrary spherical section of the universe is effectively only attracted by the matter interior this sphere

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and so is attracted to the center of the sphere. Since this applies to arbitrary spherical sections, cosmic matter pulls together by the force of gravity, according Newton.

Though perhaps intuitive (matter attracts other matter), the Newtonian view rests on the dubious assumption of instantaneous "action at a distance" in an infinite universe. Instead, we consider propagation of gravity at the speed of light in a universe of finite age, thus assume a propagating gravitational horizon. However, in the presence of a horizon, application of the shell theorem fails, therefore the Newtonian derivation collapses (cf. [7]). But actually, this is what one would expect, since due to symmetry the gravitational field in the perfectly homogeneous isotropic universe is zero everywhere, which makes the concept of deceleration by gravitational attraction questionable. The same argument applies to a "repulsive force" induced by dark energy.

Zero field points at constancy of the kinetic energy of recession; no energy is being exchanged. Within Newtonian context mass inertia is invariant, so constant kinetic energy implies constant recession velocities, i.e. a coasting universe, as pointed out earlier by Layzer [6]. This obviously can not explain the ΛCDM model.

In a Machian context however mass inertia is a relational property which depends on the "distribution of matter", and so is likely to evolve in an expanding universe. In the approach taken by Schrödinger [4], Machian kinetic energy is a relational and mutual property between any pair of point particles (m_i,m_j) and is defined

$$T_{ij} \equiv \tfrac{1}{2}\mu_{ij}\dot{r}_{ij}^2\,, \tag{2}$$

where r_{ij} denotes the proper radial distance (separation) of the particles. Crucial here is that from a relational point of view *only* radial motion is meaningful in the physical relationship of the two point particles. This ontological notion is due to Bishop Berkeley [3, 7]. Machian inertia μ_{ij} is also a relational and mutual property between any two particles and is defined

$$\mu_{ij} \;\equiv\; m_i\frac{\varphi_j(r_{ij})}{\varphi_{eff}} \;=\; m_j\frac{\varphi_i(r_{ij})}{\varphi_{eff}} \;=\; \frac{-Gm_im_j}{\varphi_{eff}\,r_{ij}}, \tag{3}$$

where the effective potential serves as a normalization parameter which preserves consistency with Newtonian inertia [7]. Since only the radial component of motion contributes to the kinetic energy between the two particles, the two perpendicular components of motion do not contribute. This implies that in any peculiar motion of a particle m relative to the cosmic sphere effectively only a fraction $\frac{1}{3}$ of the cosmic potential contributes to the inertia of the particle relative to the universe. Hence,

$$\varphi_{eff} = \tfrac{1}{3}\varphi, \tag{4}$$

as explained in more detail in [7].

Just by geometrical argument, the density of dust particles dilutes as a^{-3}. This, however, only regards the number of particles, but from a Machian perspective this is not necessarily true for the *energy* density of the dust; Eq.(3) expresses that mass inertia is a mutual property between particles and is proportional to their mutual potential

energy. This means inertial mass does not exist without the other particle. This is the radical difference with Newton's and Einstein's theory. It is a very strong notion, in light of which it appears conceivable that the energy density of dust dilutes at a rate different from a^{-3}. This applies equally to other forms of matter, as we will argue.

According [7], the Friedmann equation can be derived from the Machian energy between a (unit) test mass m and all the receding cosmic matter within the gravitational horizon. Machian kinetic energy between m and all the cosmic matter within the horizon is [7]

$$T = \tfrac{3}{4}\chi_g^2 \dot{a}^2, \tag{5}$$

where χ_g is the comoving distance to the horizon (the symbol m is omitted for simplicity). The potential energy of m due to the cosmic masses within the horizon is according the Newtonian definition, i.e.,

$$V = \varphi = -2\pi G\rho a^2 \chi_g^2. \tag{6}$$

In a strict Newtonian sense the matter density regards ordinary matter only, but here we assume the density parameter ρ includes all different types of matter. The Machian energy equation is thus

$$T + V = \tfrac{3}{4}\chi_g^2 \dot{a}^2 - 2\pi G\rho a^2 \chi_g^2 = E = const., \tag{7}$$

where we assume total energy E is a conserved quantity. Similar to the usual treatment of vacuum energy, we include total energy in the extended density parameter, i.e. $\rho_e = \rho + \rho_E$, where

$$\rho_E = E/2\pi G a^2 \chi_g^2 \tag{8}$$

is the density of total energy. Associated with this density is the potential

$$\varphi_E = -2\pi G\rho_E a^2 \chi_g^2. \tag{9}$$

Then the "extended" potential becomes

$$\varphi_e = \varphi + \varphi_E = -2\pi G(\rho + \rho_E) a^2 \chi_g^2. \tag{10}$$

The Machian energy equation (7) can be rewritten

$$\tfrac{3}{4}\chi_g^2 \dot{a}^2 \; = \; 2\pi G(\rho + \rho_E) a^2 \chi_g^2, \tag{11}$$

which is in fact the Friedmann equation

$$\frac{\dot{a}^2}{a^2} = \tfrac{8}{3}\pi G(\rho + \rho_E). \tag{12}$$

The intriguing aspect of Eq.(8) is that the identity of total energy density depends on the evolution of the horizon χ_g. For instance, if $\chi_g = const.$ then according Eq.(8)

we have $\rho_E \propto a^{-2}$, representing curvature energy, like in the Newtonian case. In a de Sitter universe, however, the proper distance to the event horizon is constant, i.e., $R_g \equiv a\chi_g = const.$, therefore $\chi_g \propto a^{-1}$, which implies $\rho_E = const.$; total energy density acts as constant vacuum energy density ρ_Λ, i.e., as a cosmological constant. Hence, to determine the actual identity of ρ_E we must identify $\chi_g(a)$.

In contrast with the Newtonian definition of the potential, Sciama [1] derived, by a gravitational analog of Maxwell's theory, a universally constant value of the cosmic potential equal to

$$\varphi_u = -c^2. \tag{13}$$

It is therefore interesting to see how Sciama's constant potential fits in, since constancy of the cosmic potential appears to be a fundamental property of spacetime, just like the universal constancy of the speed of light. The obvious question is thus how φ_u relates to the potential φ_e.

Recalling that zero exchange of energy in the homogeneous isotropic universe points at constancy of kinetic energy, the assumed conservation of total energy indeed implies that also potential energy is constant. We are thus strongly led to assume φ_e is constant, i.e.,

$$\varphi_e = k\varphi_u = -kc^2, \tag{14}$$

where $k > 0$ is a constant to be determined. Given Eq.(10) and constancy of E, it follows that $\varphi = -2\pi G\rho a^2\chi_g^2$ is constant too. Hence, the immediate consequence of this is that within the present Machian physics all types of matter-energy satisfy a common relationship,

$$\rho(a) \propto \rho_E(a) \propto a^{-2}\chi_g^{-2}(a). \tag{15}$$

This means densities dilute uniformly, at a fixed ratio. This may seem wrong, as it goes totally against the established (as good as undisputed) density-scale relations, like $\rho_r \propto a^{-4}$ for radiation and $\rho_m \propto a^{-3}$ for pressureless matter. But recall that in Machian physics energy is *not* an intrinsic property of the particle, rather it is a property of its interactions with all other particles of the universe. Therefore, it is leading that the total energy associated with this cosmic interaction is constant, instead of the un-Machian notion that isolated particles represent energy (which in fact gives rise to presumed loss of photon energy in the expanding universe, as well as creation of energy due to a cosmological constant). If energy is about cosmic interaction, then indeed the distance to the horizon is an essential parameter in the definition of energies, as above.

Anything beyond the horizon is causally disconnected from us, which is the case if we assume the proper distance to the horizon propagates away at the speed of light, i.e.,

$$\dot{R}_g = c. \tag{16}$$

Since we consider gravity propagating at the speed of light, the horizon χ_g behaves as a light front, so satisfies the condition of a null geodesic. That is, given the FLRW metric $ds^2 = c^2dt^2 - a^2d\chi^2$, the horizon propagates locally at the speed of light, i.e.,

$$a\dot{\chi}_g = \pm c, \tag{17}$$

where $+c$ holds for a particle horizon, while $-c$ applies to an event horizon. From the Machian energy equation (11) and constancy of the extended potential, Eqs.(10,14), we obtain the recession velocity (> 0) of a galaxy at (and just crossing) the horizon

$$\chi_g \dot{a} = \sqrt{\tfrac{4}{3}k}\, c. \tag{18}$$

The sum of Eq.(17) and Eq.(18) is the speed of the proper distance to the horizon, i.e.,

$$\dot{R}_g = \chi_g \dot{a} + a\dot{\chi}_g = (\sqrt{\tfrac{4}{3}k} \pm 1)\, c. \tag{19}$$

then, given Eq.(16), the only remaining choice of $k > 0$ is

$$k = 3, \tag{20}$$

while the sign of local speed of gravity must be negative. Thus recession velocity of galaxies at the horizon Eq.(18) is twice the speed of light

$$\chi_g \dot{a} = 2c, \tag{21}$$

meaning that the horizon is at twice the Hubble distance. Since by Eq.(19) the local speed of gravity must be negative to meet $\dot{R}_g = c$, i.e.,

$$a\dot{\chi}_g = -c, \tag{22}$$

we find that the horizon is an event horizon. This also follows from the solution of Eqs.(21,22), i.e.,

$$\chi_g(a) = \chi_{go} a^q, \tag{23}$$

where χ_{go} is the present value of χ_g and where q is the (constant) deceleration parameter. Substituting Eq.(23) in Eq.(22) and substituting Eq.(21) gives $-c = a\dot{\chi}_g = q\chi_g\dot{a} = q2c$, hence deceleration is constant and equals,

$$q = -\tfrac{1}{2}. \tag{24}$$

Therefore, the unique solution of $\chi_g(a)$ is

$$\chi_g(a) = a^{-\frac{1}{2}}. \tag{25}$$

Note that $\chi_g(0) = \infty$, meaning that at Big Bang all matter was causally connected and due to that we can still see last images of sources which were once within the horizon (cf. Rindler [2]), even though the horizon is at only twice the Hubble distance. Substitution of Eq.(25) in Eq.(15) yields, under the present Machian assumptions, the uniform identity of all types of matter-energy,

$$\rho(a) \propto \rho_E(a) \propto a^{-1}. \tag{26}$$

The simple cosmological model associated with this uniform matter-energy is

$$H^2 = H_o^2 a^{-1}, \tag{27}$$

where $H = \dot{a}/a$ is the Hubble parameter and H_o its present value.

Thus we find that, subject to conservation of total Machian energy and constancy of Machian kinetic energy:

i) Machian matter-energy of all types dilutes uniformly as a^{-1}, thus gives rise to a constant accelerated expansion of the universe at $q = -\frac{1}{2}$ from visible matter sources, i.e., without assuming dark mater or dark energy.

ii) In terms of the ΛCDM model $q = -\frac{1}{2}$ means $\mathit{\Omega}_m = \frac{1}{3}$ and $\Omega_\Lambda = \frac{2}{3}$, in good agreement with present observations (Planck data [5]). Nevertheless, the models deviate in the past and future because in the ΛCDM model q varies with the scale factor.

iii) Since $k = 3$, it follows that the extended potential $\varphi_e = -3c^2$. Therefore Sciama's potential φ_u coincides, not surprisingly, with the effective value of the extended potential, i.e.,

$$\varphi_u = \varphi_{e,eff} = \tfrac{1}{3}\varphi_e = -c^2. \tag{28}$$

iv) The present Machian model of Eq.(27) has several favorable properties. Total energy is conserved. It provides an explanation of accelerated expansion without invoking dark matter or dark energy. For the Machian model Eq.(27) it does not matter which fraction of the extended potential φ_e is due to dust (baryonic or dark), photons or possible other components, which appear totally interchangeable forms of energy. Furthermore, the model does not suffer from the so called "coincidence problem", i.e., the unlikely coincidence that $\Omega_m \approx \Omega_\Lambda$ at present time (as it in fact predicts $\Omega_\Lambda = 2\Omega_m$ always). Neither it needs an inflationary period to smooth out the universe after Big Bang (the "horizon problem"), since by Eq.(25) all matter of the universe was causally connected at Big Bang. Last but not least, the model satisfies the Machian principle.

References

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